The Compton Effect

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Gamma radiation from a Cs137 source was backscattered off aluminum, and the Compton effect was observed. The difference in energy between incident photons and 180° backscattered photons was determined to be 0.46 ± 0.03 MeV. This value represents a 3.6 % error from the theoretically calculated value of 0.477 MeV. The effectiveness of lead shielding was evaluated and determined to have no effect in resolving the energy of the incident and 180° degree backscattered photons.

INTRODUCTION

In 1887 Frank Hertz discovered[1] the photoelectric effect. Light shone on a piece of metal will eject electrons. This process appears to conflict classical electromagnetic theory. Light waves which carry energy in the form of oscillating electric and magnetic fields can impart enough energy to an electron so that it is ejected. However, there are features of the photoelectric effect that cannot be described classically. First, as the intensity of light is increased, the number of ejected electrons increases, but their kinetic energy remains constant. Second, below a certain frequency no electrons are ejected. According to classical theory, if the intensity of the electric and magnetic fields are increased, then these fields will impart more energy to the electrons. Thus, ejected electrons should have increased kinetic energy. Classical theory stipulates that low frequency light should be able to eject some electrons. Clearly, classical electromagnetic theory is not adequate to explain this phenomenon. A new theory of light was needed.

The work that paved the way for the modern theory of light was begun by Max Planck, who was the first to propose[1] that radiation is not a wave but rather is quantized. He came to this discovery in his study of black body radiators and determined the formula for the radiative energy density of a black body. But, in order to fit empirical data with his theory, Planck assumed that only discrete amounts of energy could be absorbed or emitted by the black body, in multiples of hf, where h is Planck's constant and f is the frequency of the radiation. Planck theorized that the composition of the blackbody itself was responsible for the quantization of energy.

In 1905, prompted by Max Planck's work on black body radiators, Einstein proposed[1] that the energy in an electromagnetic field is not distributed over a wave front but instead localized in clumps or quanta. The notion that light was a particle and not a wave ran contrary to Maxwell's equations, that describe light as an electromagnetic wave. However, this new theory explained the photoelectric effect. According to Einstein, if the intensity of light is increased, the number of photons will increase and thus eject more electrons, but each photon still carries an energy, hf. Therefore, the kinetic energy of the electrons will remain constant. The low frequency threshold can also be explained using the particle theory of light. For any metal there is a minimum amount of energy required to remove an electron. Since a photon's energy is described by hf, below a certain frequency, the photon will not have enough energy to eject an electron. Even though the particle theory of light correctly explains the photoelectric effect, it was not widely accepted. However in 1923, Arthur Holly Compton provided[1] further evidence that light should be regarded as a particle with energy and momentum.

The photoelectric effect showed that energy is conserved with a collision between a photon and an electron. In the photoelectric effect, the energy of the photon is on the same order of magnitude as the energy binding an electron to a nucleus, a few eV. Thus, when the photon strikes the electron it imparts only enough energy to eject that electron from the metal. However, if the energy of the photon is large compared to the binding energy of the electron, one could regard the electron as free. For example, x-ray photons have energy of several KeV. Therefore, both conservation of momentum and energy could be observed. To show this, Compton scattered x-ray radiation off of a graphite block and measured the wavelength of the x-rays before and after they were scattered. He discovered that the scattered x-rays had a longer wavelength than that of the incident radiation. Compton deduced that if the x-rays were regarded as particles, photons, then he could apply the laws of conservation of energy and momentum to the system. Using these laws he was able to account for and derive the correct expression for the shift in wavelength. Therefore, Compton empirically proved that light can be regarded as a particle.

THEORY

The Compton effect involves scattering high energy photons off of electrons and observing the shift in wavelength between the incident and the scattered photons. Compton theorized that if photons carry energy, they should also carry momentum. The energy (E) of a particle is related to its mass (m) and momentum (p),

$$E^2 = (pc)^2 + (mc^2)^2 \qquad (1)$$

where c is the speed of light. Since the mass of a photon is zero, its energy is $E = pc$. The energy may also be defined as $E = hf$, where h is Planck's constant and f is frequency. Using these relations, the momentum a photon is related to its wavelength (λ), $p = h/\lambda$. Compton argued that the shift in wavelength is a result of a single photon imparting momentum to a single electron. Therefore, the theory is derived from the laws of conservation of energy and momentum.

Consider a photon with energy E_0 and momentum $\mathbf{p_0}$, and a stationary electron with rest energy mc^2. When the photon collides with the electron, the electron recoils with energy E_e and momentum $\mathbf{p_e}$. The scattered photon will have an energy E and momentum **p**. By conservation of energy and momentum,

$$E_e + E = mc^2 + E_0 \qquad (2)$$

and

$$\mathbf{p_e} + \mathbf{p} = \mathbf{p_0} \qquad (3)$$

Combining energy and momentum conservation using equation (1) yields

$$\lambda - \lambda_0 = \frac{h}{mc}(1 - \cos\theta) \qquad (4)$$

The shift in wavelength is related only to the mass of the electron and the backscattered angle. The shift has no relation to the energy of the incident photon. The Compton effect can also be expressed as a shift in energy between the incident and scattered photon.

$$E - E_0 = \frac{E_0 E}{mc^2}(1 - \cos\theta) \qquad (5)$$

For a 180° backscattered photon, the shift in energy between E_0 and E is

$$E_0 - E = E_0\left(\frac{2E_0}{2E_0 + mc^2}\right) \qquad (6)$$

For Cs137, $E_0 = 0.6612$ MeV, and the rest energy (mc^2) of the electron is 0.511 MeV. Using equation 6, the theoretical value for the shift in energy between the incident and 180° backscattered photon is 0.477 MeV.

EXPERIMENTAL SETUP

A Nucleus Scintillation Counter (SC /PMT) is connected to a Nucleus Model 800 Multichannel Pulse Height Analyzer (PHA). The (SC/PMT) consists of a NaI crystal (scintillator) and a photomultiplier tube (PMT). A photon from an x-ray source strikes the scintillator which outputs light proportional to the energy of the incident photon. The light outputted from the scintillator is converted into electrical impulses via the photoelectric effect in the PMT. The height of impulses created by the PMT is proportional to the light output of the scintillator. Therefore, the resulting current pulse is proportional to the energy of the initial photon. These pulses are organized by the PHA, which categorizes the pulses according to their height. into bins according the number of impulses (counts) with a certain height (channel number). The energy scale can be determined by matching observed peaks with accepted[2] values (see Table 1 in the Data Section).

DATA

To determine the energy scale, data were collected using three x-ray sources: Cs137, Co60 and Na22.

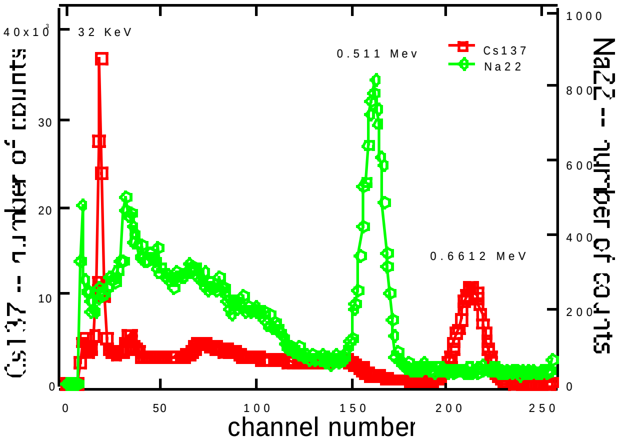

Figure 1: Reference Trials of Cs137 and Na22 used to determine the energy scale. Co60 is not on this plot because none of its major peaks fall in this energy range.

The run times and position of the observed peaks for each source with their corresponding accepted[2] energy values are presented are in Table 1.

Source	Run Time (s)	Major Peak Observed (Channel Number)	Major Peak Accepted Value (Energy)
Cs137	60	18, 212	32 KeV, 0.6612 MeV
Na22	600	162	0.511 Mev
Co60	300	--,--	1.17 MeV, 1.33 MeV

Table 1: Table denoting run times as well as the position of the observed and accepted[2] values for the major peaks.

Data was then taken with the Cs137 source sandwiched between an aluminum block and the PMT.

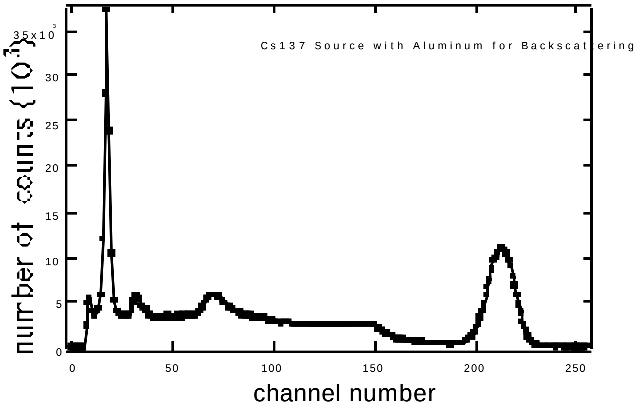

Figure 2: Figure showing one trial using a Cs137 sample and Al for backscattering

The far right peak in Figure 2 corresponds to the incident photons. Channel number ~150 corresponds to the Compton shoulder and then the next peak at 70 ± 2 is the backscattered peak. The large peak on the left corresponds to the 32 KeV peak. Next, the Al was removed, being careful not to change the location of the Cs137 source and another run was completed using the subtract feature on the PHA. The subtract feature works as follows, each time a count in registered by the PHA, it is subtracted from the number of counts in memory. The backscattered peak is identified as the highest peak because the rest of the peaks are subtracted out. This procedure was repeated three times to insure reproducibility

Several trials were completed to determine the effectiveness of lead shielding to block photons other than the incident and 180° backscattered photons. Six, one centimeter thick Lead blocks were placed between the source and PMT. Three were place on either side of the center of the Cs137 source so that a narrow slit existed where the radiation could pass through.

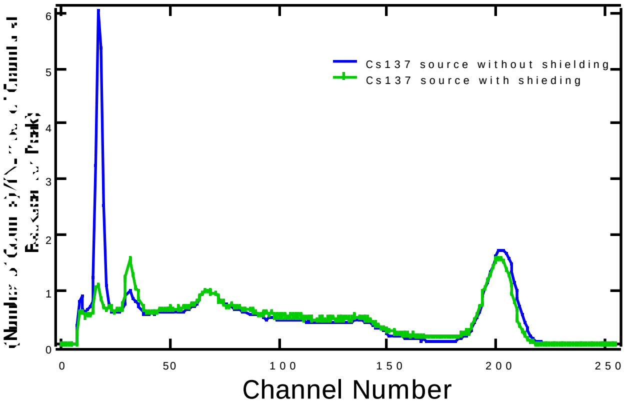

Figure 3: Plot of Cs137 source with and without shielding. (Number of Counts)/(Number of Counts at Backscattered peak) is plotted versus channel number to compare the position and width of the backscattered peaks.

Lead shielding did decrease the overall height of all the peaks. It had the greatest effect on the low energy (32 KeV) peak. Also it is interesting to note that the peak around channel 35 increased with respect to the surrounding peaks when the shielding was in place. Figure 3 reveals that lead shielding had no effect on resolving the incident and 180° backscattered photons. The position and width of the backscattered peak did not change when shielding was added because the backscattered peak is at an higher energy where lead shielding is ineffective. The incident peak is slightly shifted; however, this effect is quite small.

RESULTS AND DISCUSSION

For the reference trials, plots of number of counts at a certain energy versus channel number

(Figure 1) were analyzed to determine the position of the major peaks (see Table 1). The plot of accepted energy versus channel number (Figure 4) was used to create an equation that converts channel number to energy.

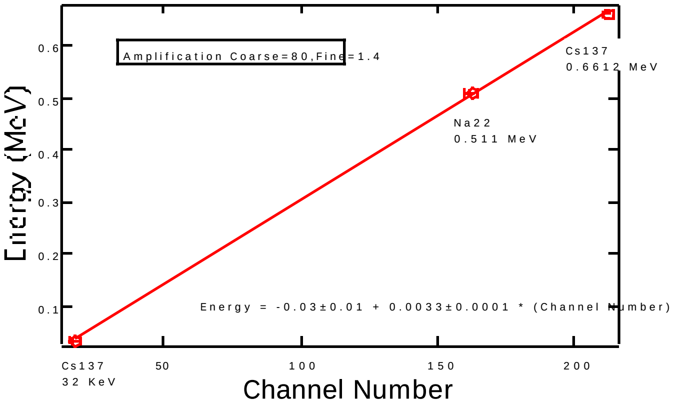

Figure 4. Plot of accepted value of energy for the major peaks versus observed channel number for the Cs137 and Na22 source.

Using the line fit in Figure 4, the equation for energy (E_c) as a function of channel number (CN) was determined,

$$E_c = (-0.03 \pm 0.01) + (0.0033 \pm 0.0001) * CN \qquad (8)$$

Using this equation, low Channel Numbers (<8) will correspond to a negative energy. This zero energy was observed in all the trials. Zero energies are observed because the first channel on the PHA does not correspond to zero energy.

The shift in energy between the incident and backscattered photon (Figure 2) was determined to be 0.46±.03 MeV. This value represents a 3.6 % error from the theoretically calculated value of 0.477 MeV.

The shift in energy of the backscattered photon is a function of angle. This angle is defined as the angle between the incident and backscattered photon. This experiment was carried out to measure the shift in energy between incident and 180° backscattered photons. Therefore, lead shielding was put in place to block photons other than the incident and 180° backscattered photons from striking the PMT. Lead shielding did effect the height of some peaks. It is expected that lead shielding would be more effective blocking low energy photons and this was observed by the drastic decline of the 32 KeV peak. But the relative increase of the peak at ~35 channel contradicts the expectation that the shielding is more effective blocking low energy photons. An explanation for this increase is yet to be determined. Despite the ability of the shielding to decrease the overall heights of the lowest energy peaks, shielding was ineffective helping resolve the energy of the incident and the 180° backscattered photons.

CONCLUSION

The Compton effect was observed using gamma radiation from a Cs137 source and aluminum for backscattering. The shift in energy was determined to be 0.46±.03 MeV. This value represents a 3.6 % error from the theoretically calculated value of 0.477 MeV. The lead shield used to try to isolate 180° backscaterred photons was observed to block some photons. However, it had no effect in resolving the energy of the incident and 180° backscattered photons. Data collected without shielding is in good agreement with theoretical calculations. This technique is effective in measuring the shift in energy. This result verifies Compton's theory that photons are particles that have energy and momentum. Further work should monitor the shift in energy as a function of θ as well as using other x-ray sources.

ACKNOWLEDGEMENTS

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REFERENCES

[1] John R. Taylor and Chris D. Zasfiratos, Modern Physics for Scientists and Engineers, (Prentice Hall, Englewood Cliffs, New Jersey 1990), pp. 117-121.

[2] R.L. Heath, Scintillation Spectrometry: Gamma-Ray Spectrum Catalogue, 2nd Edition, (Phillips Petroleum Company August 1964).